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LET THE SUN SHINE IN

International collaboration yields a high-performance EUV spectrometer for Solar-B spacecraft.

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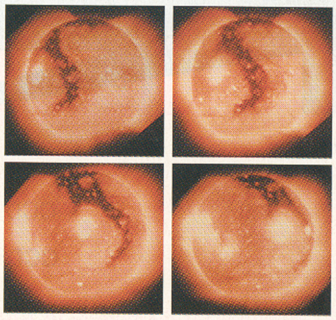
In 2005, the Institute of Space and Astronautical Science (ISAS) will launch Solar-B, a spacecraft designed to observe the solar atmosphere with high spatial and spectral resolution at visible and x-ray wavelengths, using an array of instruments that includes the Extreme-ultraviolet Imaging Spectrometer (EIS). The scientific objective of the mission is to uncover the physical mechanisms responsible for heating the solar corona and causing explosive solar phenomena such as solar flares and coronal mass ejections.

Recent spacecraft imaging instruments have revealed a morphologically complex and dynamic solar atmosphere that can wreak havoc in the near-Earth space environment via intense x-ray and particle emissions. These emissions can cause severe damage to commercial power grids and the electrical systems of orbiting satellites, disrupt military communications systems, affect the Earth's atmospheric drag on satellites, and pose a serious threat to astronauts. So understanding the behavior of the highly ionized gases (plasma) in the sun's atmosphere, and the intimate connection of these gases to the sun's magnetic field, is



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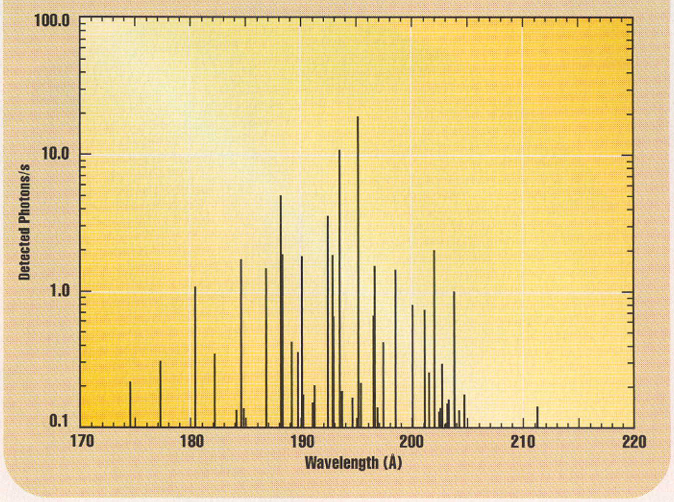

Figure 1 The theoretical spectrum of the EIS short wavelength band shows key spectral lines expected from quiet Solar regions, i.e., regions with no large-scale dynamic activity.

of more than purely scientific interest.

In addition, the sun's atmosphere poses extremely interesting problems in magnetohydrodynamics (MHD) and fundamental plasma physics that have important implications for a wide range of astrophysical and geophysical problems. For these reasons, there is a large international interest in studying the sun. This is reflected in the Solar-B mission, which includes instruments from three countries: Japan, the United States, and the United Kingdom.

EUV spectrometry

The temperature of the solar atmosphere ranges from about 5500 K (corresponding to visible light) to millions of degrees (corresponding to x-ray radiation). For this reason it is necessary to study the sun using instruments sensitive to radiation over a broad range of wavelengths. Spectroscopic observations are particularly important because they allow detailed determinations of plasma parameters such as temperature, density, and element abundance from measurements of the absolute intensities and intensity ratios of spectral lines. Furthermore, using the Doppler effect, determination of line-of-sight bulk flows and nonthermal turbulent motions are also possible from measurements of the wavelength positions of spectral lines and the shapes of the line profiles, respectively.

To interpret all of these observations, we must obtain spectroscopic measurements for many positions within individual structures that can be identified in pure imaging experiments. Because conventional stigmatic spectrometers usually employ an entrance slit to define the shape of a spectral line, the image produced by a single high-resolution spectrum is frequently very narrow (1 arc sec or 730 km at the sun's distance) in the direction of dispersion. For this reason, in addition to the relatively low sensitivity of most previous high-resolution solar spectrometers, it has been impossible thus far to obtain high-resolution spectra for significant areas of the sun's atmosphere at sufficient time resolution to adequately test theoretical models. The Solar-B EIS is designed to overcome these observational difficulties.

EIS is one of the first of a new generation of spectrometers designed to provide high-resolution spectra at high time cadence for areas of the sun that are large enough to allow scientists to understand what type of structures are being observed. The EIS instrument captures data over two narrow wavelength regions in the extreme ultraviolet (EUV), which contain many spectral emission lines important for plasma diagnostics (see figure 1). These lines are emitted by "cool" ions such as helium II (formed at about 10^5 K in the solar transition region), coronal ions such as iron (Fe) XII (emitted near 10^6 K), and flare ions such as Fe XXIV (emitted at temperatures as high as 20×10^6 K). The instrument provides images of active-region magnetic-loop structures in 3 to 10 s with 2 arc sec spatial resolution. The images are at a spectral resolution sufficient to measure Doppler wavelength shifts of about 2 km/s and nonthermal motions of about 20 km/s.

inside the EIS

EIS consists of an all-reflective (off-axis) two-component design that maximizes spectral and spatial resolution; multilayer coatings on the optics that greatly enhance reflectivity; a composite-fiber structure that is lightweight and maintains tight mechanical tolerances with temperature variation; an EUV-sensitive CCD camera with high spatial resolution; and a sophisticated contamination-control plan. Although each of these items has been successfully used before in space experi-

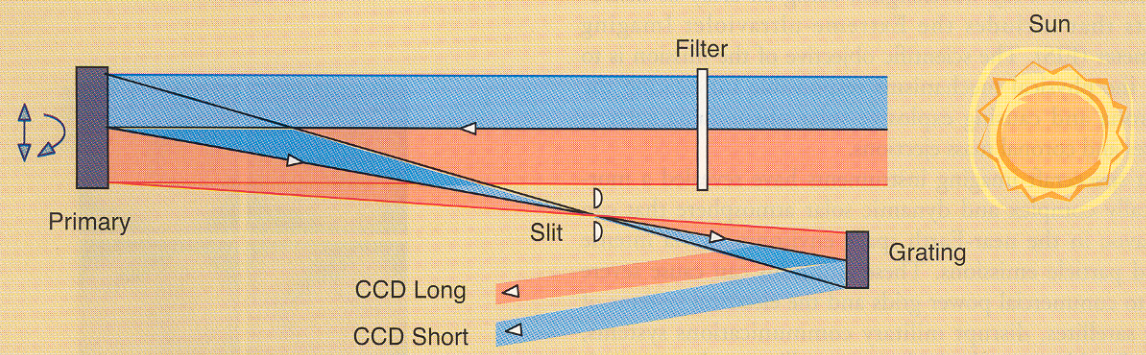

Figure 2 A simplified schematic of EIS shows entrance filter, telescope mirror, grating, and CCD detectors. Short and long refer to the short and long wavelength bands, respectively. The vacuum enclosure for the fragile entrance filter is not shown.

ments, it is the simultaneous usage in a single spectrometer that is unique in solar spectroscopy.

In the EIS, light from the sun enters the instrument by first passing through an aluminum filter on an electro-formed mesh (see figure 2). This filter rejects unwanted visible light and heat. Because the mounted filter is fragile, it is enclosed in a small vacuum enclosure "clam-shell" (not shown). This enclosure contains two doors that are opened after launch by paraffin actuators, allowing the light to pass through the entrance filter and impinge on an articulated telescope mirror.

The function of the mirror is to image a portion of the sun on the entrance slit of the spectrometer. By moving the mirror in either coarse or fine steps, the slit of the spectrometer can be effectively rastered over a solar area to construct a 2-D image of the area (taking into account spacecraft motions). The telescope mirror is an off-axis paraboloidal Zerodur mirror with a 15-cm diameter clear aperture and a 1.938-m focal length. The surface is super-polished to better than 5 Å rms micro-roughness and contains two different silicon/molybdenum (Si/Mo) multilayer stacks applied over D-shaped segments of its surface. One multilayer coating is designed to optimize reflectivity over wavelengths ranging from 184 to 204 Å; the other coating maximizes reflectivity over wavelengths ranging from 250 to 290 Å. Thus, a single mirror provides high reflectivities in two wavelength regions that could not be covered in the bandpass of a single multilayer coating. One-half of the mirror is optimized for each bandpass. Peak reflectivity within each band is about 30%.

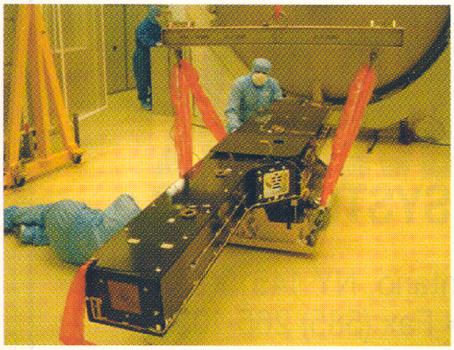
UB/MSSL

Figure 3 The mechanical/thermal engineering test model of the EIS structure undergoes tests in the UK.

The spectrometer has four interchangeable slits. The slit mechanism also contains a mechanical shutter that regulates the exposure times for the CCD detector. Two narrow slits with dimensions of 1 arc sec × 512 arc sec and 2 arc sec × 512 arc sec can be selected. The other two slits are really much wider slots measuring 40 arc sec × 512 arc sec and 250 arc sec × 512 arc sec. The slots are used to produce monochromatic images of the sun within the field-of-view of the slot dimensions. As captured, the slot images are convolved with Doppler motions in the direction of dispersion of the grating, but enough is known of solar phenomena to deconvolve, in many cases, the Doppler and spatial components of the images.

EUV radiation from a slit or a slot passes through another thin aluminum filter and then illuminates a 9-cm diameter, ion-etched, holographic toroidal grating. Designed with uniform line spacing, the laminar-ruled grating features a 1.18-m radius of curvature and a ruling density of 4200 l/mm. The telescope slit/grating combination results in a 1.4X magnification of the mirror's approximately 0.1 arc sec/μm plate scale that gives a good match between the 10-μm-wide narrow slits and the 13.5-μm CCD pixel dimension. The plate scale is 1 arc sec/pixel, which results in about 2 arc sec spatial resolution for solar structures.

A geometric optics study of the optical system shows that the theoretical blur is less than 0.5 arc-sec for all angles less than 10 arc min from the optical axis (and less than 0.75 arc sec for 15 arc min). The grating is also divided into two D-shaped segments, each of which is coated with one of the Si/Mo multilayer configurations. The grating has a focusing mechanism for adjusting the focus in orbit.

The optics, the mechanisms for moving the optics, the corresponding mechanism and heater control electronics, and the filters are the responsibility of the Naval Research Laboratory (NRL; Washington, D.C.). The slits and the optical coatings are provided by Goddard Space Flight Center (Greenbelt, MD). Calibration of the optics and multilayer coatings will be carried out at NRL. NRL project scientists will measure reflectivities of the mirror and grating as a function of position over their entire surface areas, using the synchrotron at Brookhaven National Laboratory (Upton, NY).

The camera system consists of two multi-pinned-phase structure 1024 × 2048-pixel CCDs. The passively cooled CCDs operate at temperatures less than about 50°C. The efficiency of these CCDs is about 80%, which is far higher than the efficiency of the films used in many previous high-resolution spectrometers. These CCDs are a substantial improvement over the detectors used on the Solar and Heliospheric Observatory spectrometer, which has comparable spatial and spectral resolution.

The CCD camera system and the overall Instrument Control Unit are supplied by the Mullard Space Science Laboratory (MSSL; Dorking, UK). This laboratory also provides overall management of EIS and interfaces between the EIS team and ISAS.

design challenges

The high spatial and spectral resolution of the EIS optical system requires a structure with a very low coefficient of thermal expansion. In addition, there is a spacecraft requirement that the 3-m EIS be as lightweight as possible. These requirements and instrument properties dictate that the structure be built using a composite fiber material. The material selected is M55J/RS3 cyanate. This material has the required strength, rigidity, and lightweight properties necessary for EIS. Fabrication of the structure is the responsibility of the University of Birmingham (UB; Birmingham, UK), which is working with McLaren Composites (Shalford, UK) to develop the components. The large-panel components have carbon-fiber-composite face sheets with aluminum honeycomb cores, and all the components are assembled at UB (see figure 3).

The integration and end-to-end calibration of EIS is the responsibility of Rutherford Appleton Laboratory (RAL; Chilton, UK), again with overall management by MSSL. RAL is also responsible for contamination studies, which coordinate input from the entire EIS team.

The successful realization of EIS should result in major new discoveries and insights into the physics of the solar atmosphere. One physical process that will be investigated is magnetic reconnection, a process whereby the solar magnetic field changes its topology, resulting in a release of energy that is believed to heat the atmosphere. Magnetic reconnection should produce telltale jets of moving plasma at high temperature that we hope to detect with EIS. Another interesting topic is the dynamics of plasma confined to magnetic flux tubes. The ability to measure temperatures, densities, and motions as a function of position within flux tubes at a few seconds time resolution will provide a significant advance in our understanding of how plasma evolves in the flux tubes. The launch of Solar-B is a much-anticipated milestone in solar physics. **oe**

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